/N-34

1716

P8

NASA Contractor Report 187053

Cool-Down and Frozen Start-up Behavior of a Grooved Water Heat Pipe

(NASA-CR-187053) COOL-DOWN AND FROZEN START-UP BEHAVIOR OF A GROOVED WATER HEAT PIPE Final Report (Sverdrup Technology) 8 p

N91-19376

CSCL 20D

Unclas

G3/34 0001716

Jong Hoon Jang

Sverdrup Technology, Inc.
Lewis Research Center Group
Brook Park, Ohio

December 1990

Prepared for
Lewis Research Center
Under Contract NAS3-25266

NASA

National Aeronautics and
Space Administration

COOL-DOWN AND FROZEN START-UP BEHAVIOR OF A GROOVED WATER HEAT PIPE

Jong Hoon Jang
Sverdrup Technology, Inc.
Lewis Research Center Group
Brook Park, Ohio 44142

ABSTRACT

A grooved water heat pipe was tested to study its characteristics during the cool-down and start-up periods. The water heat pipe was cooled down from the ambient temperature to below the freezing temperature of water. During the cool-down, isothermal conditions were maintained at the evaporator and adiabatic sections until the working fluid was frozen. When water was frozen along the entire heat pipe, the heat pipe was rendered inactive. The start-up of the heat pipe from this state was investigated under several different operating conditions. The results show the existence of large temperature gradients between the evaporator and the condenser, and the moving of the melting front of the working fluid along the heat pipe. Successful start-up was achieved for some test cases using partial gravity assist. The start-up behavior depended largely on the operating conditions.

INTRODUCTION

The heat pipe, which can effectively transport a large amount of heat energy, has received much attention for space applications such as elements of space heat rejection systems and heat receivers for solar dynamic space power systems. However, heat pipes with alkali-metal working fluids and some non-metallic working fluids which may be in the frozen state prior to start-up are inoperative until the working fluid has completely melted. While the working fluid is melting, liquid in the wick structure is insufficient to handle full heat transport capability. Therefore, heat should be added carefully at the evaporator section to avoid dry-out of the wick structure. Successful start-up, which means the entire heat pipe becomes operational, is critical in obtaining the inherent advantages of heat pipes.

The studies on start-up for the metallic heat pipe were summarized based on archival literatures by Jang et al. (1990). For water heat pipes, successful start-up from the frozen state has been achieved by Deverall et al. (1970) and Kessler (1971). Start-up failure for the water heat pipe was reported by Neal (1967). Previous efforts simply attempted successful start-up from the frozen state but did not investigate the process comprehensively. Therefore, existing reports on experimental results for start-up from the frozen state are insufficient to provide an understanding of the process and to compare them with numerical simulations. Most heat pipes tested in earlier start-up tests had screen wick structures, and no tests for the grooved heat pipe were found in archival literature. Furthermore, no studies for cool-down from the steady state to below the freezing temperature of the working fluid were found.

This paper presents the experimental results of cool-down and frozen start-up tests of a grooved water heat pipe. In these tests the amount of the working fluid in the heat pipe was fixed and during the cool-down period the working fluid frozen at the condenser could not return to the evaporator. Therefore, the distribution of the working fluid in the solid state was not uniform along the heat pipe. Since this condition may play an important role in the start-up process, the cool-down from the steady state as well as the start-up process from the frozen state was tested under several different operating conditions to determine the effects on start-up rate and start-up success.

EXPERIMENTAL TEST SETUP

A water heat pipe (Jang, 1990) with axial grooved wick was used to study the cool-down and start-up process. The total length of the heat pipe is 1 m, and the length of the condenser section is 28.6 cm. The length of the condenser section is fixed but the lengths of the evaporator and adiabatic sections are variable due to operating five electrical resistance heaters independently. The outer and inner diameters of the heat pipe are 5 cm and 4.66 cm, respectively. The heat pipe shell is made of copper, with 120 axial grooves cut on the inner surface.

Five flexible, electrical heaters with a rectangular shape were tightly wrapped on the surface of the evaporator with stretch tape. The thin, flat heating element in the heater is insulated by silicone rubber. The total thickness of the heater is .0508 cm. Thus, the thermal mass (9.5 gm) of each heater is very small as needed for transient experiments. The heater can provide uniform heat flux. The length and width of each heater are 15.95 cm and 5.72 cm, respectively. Each of the 53.1 ohm heaters was connected to a power supply unit and an electrical switch was installed between each heater and the power supply unit so that each heater could be operated independently. The length of the evaporator section could be varied in fixed increments, based on the number of active heaters for each experiment. Consequently the length of the adiabatic section also varied, since the condenser length remained constant. This type of heater installation provided flexible heat input configurations on the heat pipe. Voltmeters and ammeters were installed to get exact electrical power output from the power supply units.

Sixteen copper-constantan thermocouples were installed on the outer surface of the heat pipe and two thermocouples were mounted at the center of the evaporator and condenser end caps. Temperatures measured from these end caps would be closest to the vapor temperature in the heat pipe, because one side of these thin caps is insulated and another side is in contact with the vapor space in the heat pipe. A data logger (Fluke 2280A) was linked with a computer (IBM-AT) to record temperatures by using data acquisition software (Fluke Prologger). Temperatures were recorded at each minute from 20 thermocouples.

The cooling coil, made of .435 cm outer diameter soft copper tube, was tightly wrapped on the surface of the condenser section and was held in place by stainless steel clamps at each end. A flow meter was installed at the inlet of the cooling coil, to measure coolant flow rates, and to a chiller as shown in Figure 1. Since the heat pipe was to be cooled to below the freezing temperature of water, a mixture of 50 percent water and 50 percent Ethylene Glycol was used for the coolant. The viscosity of the coolant changed significantly with temperature in the operating temperature range so that the flow meter was calibrated at several temperatures (260, 270, 280, and 296 K). During the cool-down period, coolant flow rate changed from 21.6 ml/s at the ambient temperature to 11.37 ml/s at 260 K with the valve open fully. The chiller unit has an electric controller which keeps the coolant at the desired operating temperatures within a ±1.5 K error band. Two copper-constantan thermocouples were used to measure coolant inlet and outlet temperatures.

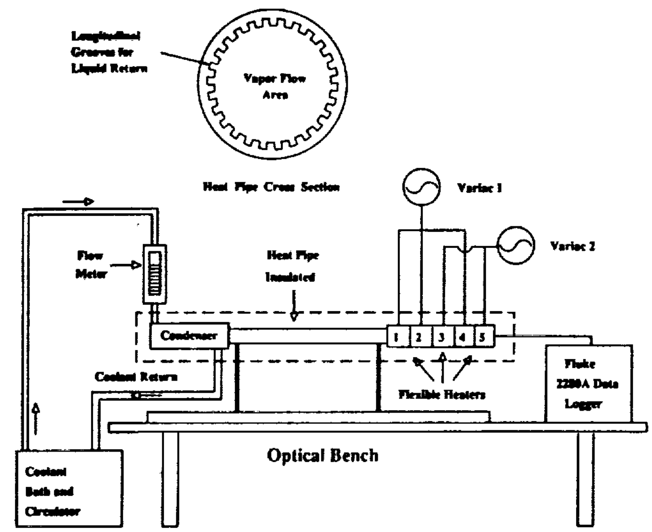

Figure 1. Schematic of test setup for the grooved copper-water heat pipe.

The water heat pipe was leveled accurately by using an optical bench. For some tests the heat pipe was inclined at an angle of + 1.2 degrees thus raising the condenser above the evaporator, in order to provide partial gravity assist for the liquid return. Insulation material made of ceramic fibers was wrapped on the entire heat pipe to a 3.81 cm thickness. The thermal conductivity of this insulation material is .03 W/m-C.

RESULTS AND DISCUSSION

The water heat pipe was initially at ambient temperature and was cooled down to below the freezing temperature of water to conduct start-up tests from the frozen state. The condenser section was cooled without heat input at the evaporator section by circulating coolant through the cooling coil wrapped on the condenser section. Figure 2 shows temperature distributions along the heat pipe length for different times during the cool-down. Isothermal conditions were maintained at the evaporator and adiabatic sections until the working fluid was frozen.

Between 20 and 25 minutes, temperature drop at the evaporator and adiabatic sections was less than that just before and after this period, and temperatures at the condenser section were below the freezing temperature of water. This indicates that water at the condenser section was freezing; therefore, the latent heat of fusion was being removed at the condenser section so that less heat was extracted from the evaporator and adiabatic sections. Also, between 30 and 35 minutes, temperatures at the evaporator and adiabatic sections had dropped to the freezing temperature of water (shown by dashed line) and further temperature decrease was small. This indicates that the working fluid at the evaporator and adiabatic sections was also

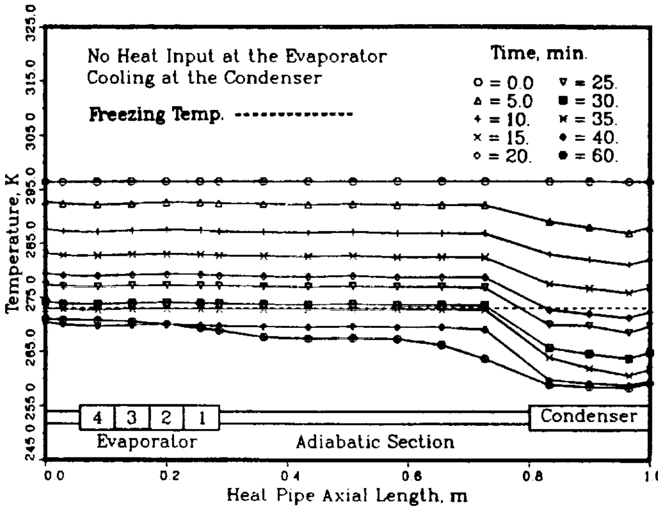

Figure 2. Axial temperature distributions during the cool-down.

freezing. Then, the temperature decreased uniformly still further, probably due to sublimation of the frozen working fluid at the evaporator and adiabatic sections. While the condenser section was cooled continuously, temperature gradients developed along the heat pipe. Temperatures near the condenser section decreased but the evaporator section did not decrease. This means that the working fluid was completely frozen and the vapor density was small; thus the heat pipe operation had ceased completely.

After the working fluid was frozen completely, start-up was attempted under various operating conditions, as summarized in Table 1. For case 1, 10 watts of heat input

Table 1. Summary of heat pipe tests.

Case No.	Maximum Heat Input (W)	Cooling During Thawing	Elevation of Condenser End
1	10	No	No
2	10	Yes	No
3	20	No	Yes[b]
4	40[a]	No	Yes[c]
5	40[a]	No	Yes

a : Heat input was 20 watts for 60 minutes, and then increased to 40 watts.
b : The condenser end was elevated after dry-out occurred at the evaporator.
c : The condenser end was elevated only during the start-up period.

were applied at the evaporator by using heater 4 without circulating coolant at the condenser section. Figure 3 shows temperature distributions along the heat pipe during the start-up period and Figure 4 shows temperature

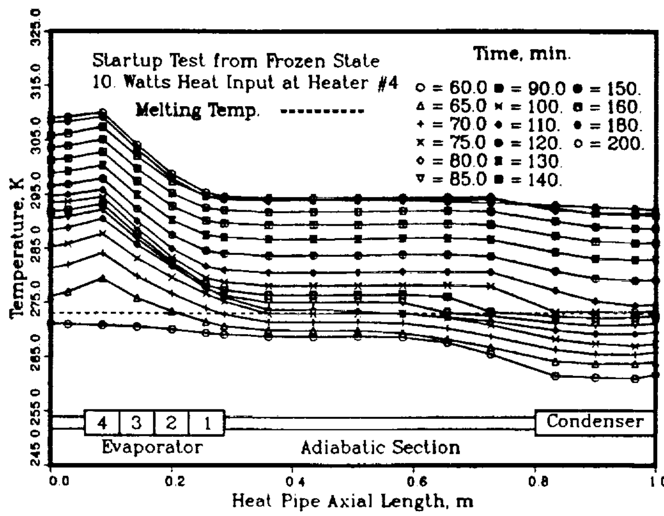

Figure 3. Axial temperature distributions during the start-up period for case 1.

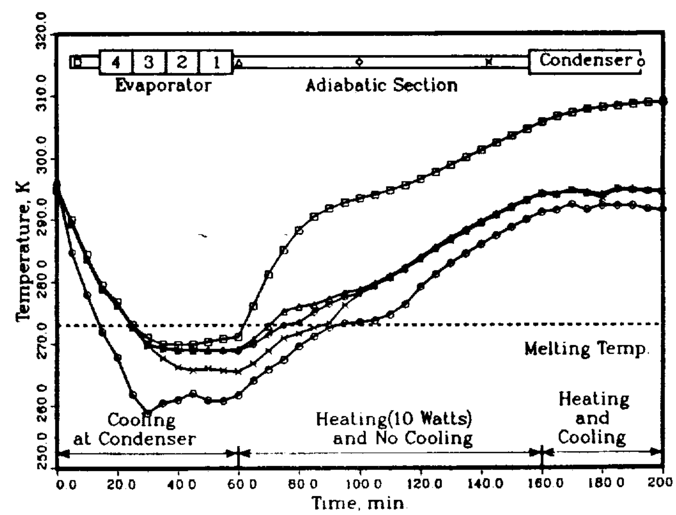

Figure 4. The operating conditions and temperature variations of the heat pipe for case 1.

variations at several locations of the heat pipe during the cool-down and start-up periods. Since the working fluid was in the frozen state, heat transfer from the evaporator section is by axial conduction through the heat pipe wall and working fluid until part of the heat pipe becomes active. So, temperatures near heater 4 were increasing rapidly, and then the temperature increase slowed down as more working fluid melted. Some heat leakage through the insulation could have caused the heat pipe to warm at the adiabatic and condenser sections before heat was transferred from the evaporator section. The front of the active section of the heat pipe was moving toward the end of the condenser section as shown Figure 3. When the start-up was achieved successfully, cooling at the condenser started to reach the steady state condition. At steady state, a relatively large temperature gradient between the evaporator and adiabatic sections existed.

For case 2, to minimize the effect of heat leakage through the insulation, cooling at the condenser was continued until the melting front reached the middle of the heat pipe while 10 watts of heat was being added at the evaporator. Then, cooling was terminated because the further cooling could remove heat added at the evaporator. Figure 5 shows the variations of temperatures at the several locations on the heat pipe. While cooling at

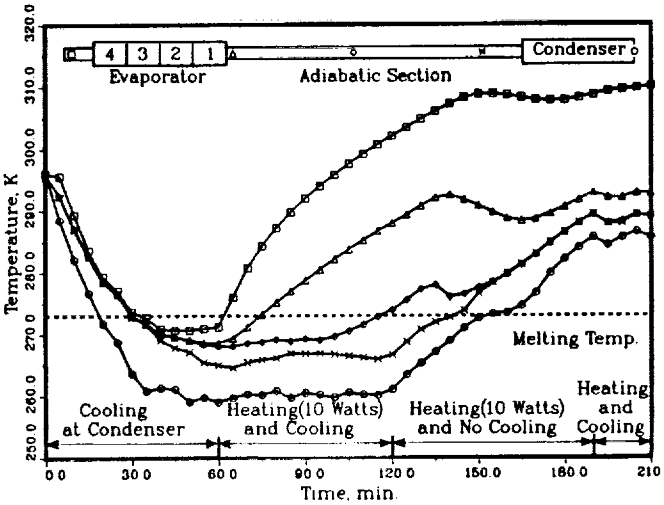

Figure 5. The operating conditions and temperature variations for case 2.

the condenser was continued, temperatures at the adiabatic and condenser sections were not increased. Large axial temperature gradients were developed and the start-up rate was slow. When cooling was terminated, the start-up speeded up. As the melting front of the working fluid neared the condenser section, temperatures adjacent to this region decreased. This phenomenon appeared at regions further away from the condenser section as the melting front moved toward the condenser end. This indicates that the excessive working fluid that accumulated during the cool-down was being returned.

For case 3, the effect of large amount of heat input at the evaporator was investigated. Twenty watts of heat was added by using heaters 3 and 4. Figure 6 shows temperature variations at the several locations on the heat pipe and the operating conditions. The start-up process was not improved with large heat input. Temperatures at the evaporator increased rapidly during the start-up. When cooling at the condenser section resumed, temperature at the evaporator continued to increase, and large temperature gradients existed between the evaporator and adiabatic sections. During this period, temperatures at other sections reached the steady state conditions. Similar phenomena were reported by the author (1990), under conditions indicative of dry-out of the wick structure at the evaporator. In an effort to achieve successful

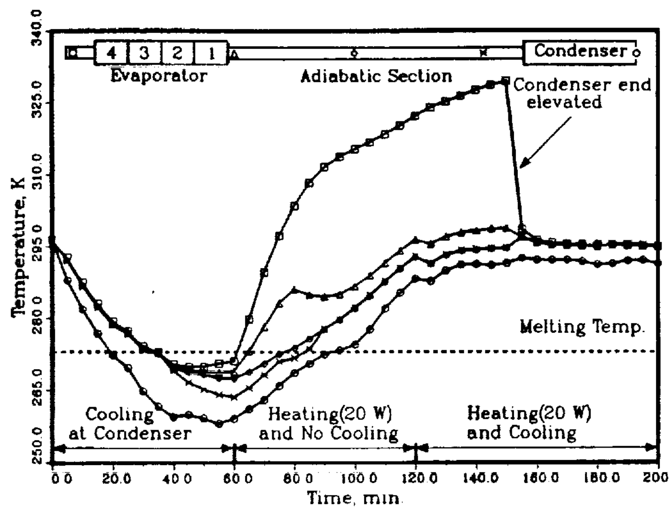

Figure 6. The operating conditions and temperature variations for case 3.

restart the end of the condenser section was elevated by 1.19 degree angle to give gravity assistance for liquid returning. Then temperatures at the evaporator section decreased rapidly and isothermal conditions were obtained at the steady state. This confirms that relatively large heat input did not increase the start-up rate but actually cause dry-out of the wick structure.

For case 4, the end of the condenser section was elevated before heat was added at the evaporator. Therefore, the working fluid melted and could be returned easily to the evaporator section. Heat input of 20 watts was applied by using heaters 3 and 4. In Figures 7 and 8, temperature distributions for this case show evidence of the working fluid returning i.e. successful restart. The

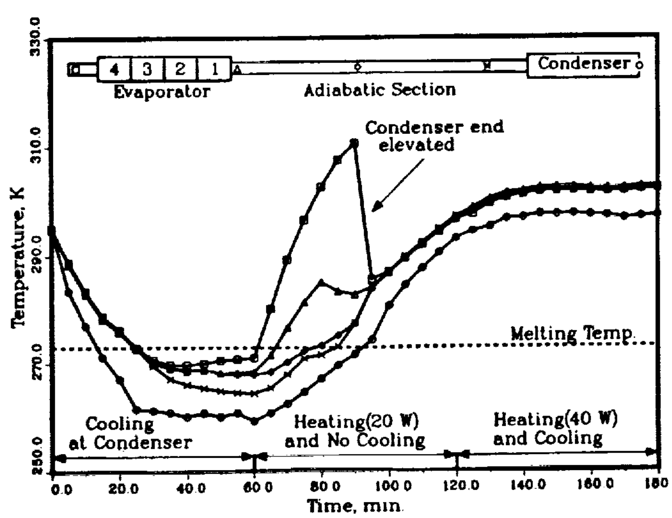

Figure 7. The operating conditions and temperature variations for case 4.

temperatures at the evaporator rose rapidly as in case 3. When the melting front of the working fluid reached the condenser section,

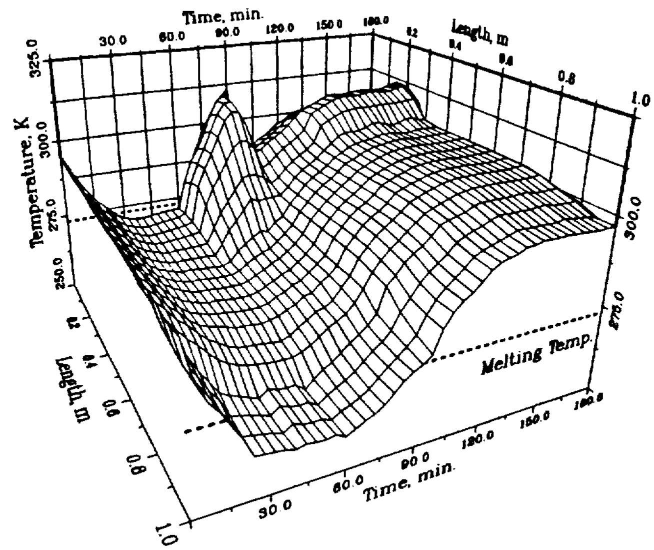

Figure 8. Surface temperature distributions during the cool-down and start-up periods for case 4.

isothermal conditions quickly developed at the evaporator and adiabatic sections. Thus, the working fluid frozen at the condenser section was apparently returned to the evaporator immediately after being melted. Hence, even with the condenser end elevated, the start-up rate was not speeded up until the working fluid at the condenser section was melted. This implies that the start-up process cannot be improved unless a sufficient amount of working fluid stays at the evaporator and adiabatic sections.

For case 5, the end of the condenser section was elevated prior to cooling and heating to provide enough working fluid at the evaporator section during the cool-down as well as the subsequent start-up periods. During the cool-down period, temperature at the evaporator approached to the freezing temperature of water asymptotically as shown in Figure 9. Then, temperatures at the

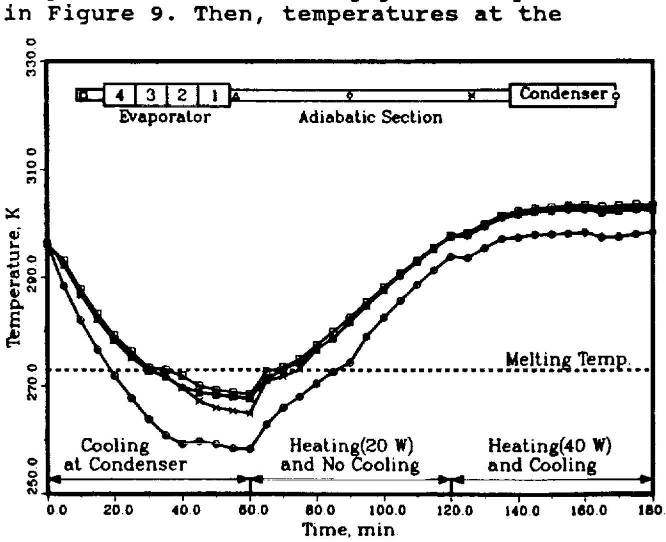

Figure 9. The operating conditions and temperature variations for case 5.

evaporator section continued to decrease, unlike those cases, when the condenser section was not elevated. When heat input of 20 watts was added at the evaporator by using heaters 3 and 4, temperatures at the evaporator section were not increased rapidly. Isothermal conditions at the evaporator and adiabatic sections were maintained. The frozen working fluid melted rapidly, resulting in improved start-up. This indicates that sufficient working fluid was at the evaporator section. Therefore, for this case, heat input at the evaporator section melted and vaporized the working fluid without dry-out, so that a large amount of heat could be transported from the evaporator to the cold region. The partial gravity assist due to the favorable tube inclination insured that enough fluid was returned to the evaporator for successful start-up. When successful start-up was achieved, additional heat input of 20 watts was applied by using heaters 1 and 2 while the condenser section was cooled. The heat pipe reached the steady state condition, after 180 min.

Figure 10 shows comparisons of the moving melt fronts as a function of time for cases 1, 2, 3, 4, and 5. The melting process of the

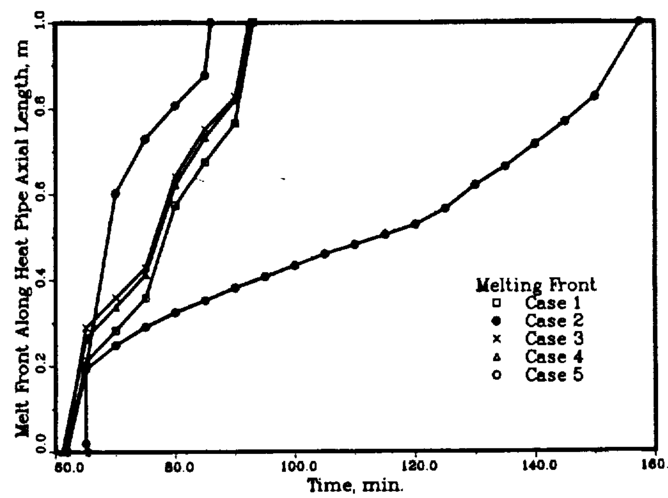

Figure 10. Comparisons of the locations of the melting front for cases 1, 2, 3, 4, and 5.

frozen working fluid was significantly slowed down with continuous cooling at the condenser section. Hence about 100 minutes was required for the melting front to reach the condenser as shown for case 2. With large heat input in cases 3 and 4, the frozen working fluid at the evaporator section melted fast but overall melting time was the same. In case 5, the melting of the frozen working fluid was the fastest among all cases tested, indicating that proper distribution of the working fluid along the heat pipe played an important role in the start-up process.

Since the working fluid at the condenser section was frozen first, the liquid working fluid could be accumulating on the frozen working fluid at the condenser without returning to the evaporator as cooling continued. Even before the working fluid started to freeze, the capillary pumping capability could be decreased because of increasing viscosity. Thus, the evaporator and adiabatic sections may not contain a sufficient amount of the working fluid and the working fluid may not be evenly distributed along the heat pipe.

CONCLUDING REMARKS

Experimental tests of a grooved water heat pipe were conducted during the cool-down and start-up periods. The heat pipe was cooled down to below the freezing temperature of water. During the cool-down, near isothermal conditions were maintained at the evaporator and adiabatic sections until the heat pipe reached an inactive state. Comparison of the experimental results with the condenser end elevated and horizontal shows that during cool-down the working fluid could not be distributed evenly along the heat pipe unless the condenser was elevated. With elevation of the condenser end, successful start-up was achieved. During the start-up, continuous cooling at the condenser section significantly delayed the start-up process.

ACKNOWLEDGEMENT

The author is indebted to Dr. A. Faghri for providing a water heat pipe to test. Also, author thanks K. Baker, F. Calfo, A. Juhasz and W. Lucas for helpful comments and assistance in experimental setup.

REFERENCES

Deverall, J. E.; Kemme,J. E.; and Florschuetsz, L. W.: 1970, "Sonic Limitations and Start-up Problems of Heat Pipes," Los Alamos RT. LA-4518.

Jang, J. H.; Faghri, A.; Chang, W. S.; and Mahefkey, E. T.: 1990, "Modeling and Analysis of a Frozen Heat Pipe from the Start-up Condition," ASME Journal of Heat Transfer, Vol. 112, No. 3, pp. 586-594.

Jang, J. H.: 1990," Transient Characteristics of a Grooved Water Heat Pipe with Variable Heat Load," NASA CR-185280 and ASME Paper No. 90-WA/NE-1.

Kessler, S. W. Jr.: 1971, "Transient Thermal Impedance of a Water Heat Pipe," ASME Paper No. 71-WA/HT-9.

Neal, L. G.: 1967, "An Analytical and Experimental Study of Heat Pipes," TRW RT. 99900-6114-R000.

NASA
National Aeronautics and Space Administration

Report Documentation Page

1. Report No. NASA CR-187053	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Cool-Down and Frozen Start-up Behavior of a Groved Water Heat Pipe		5. Report Date December 1990
		6. Performing Organization Code
7. Author(s) Jong Hoon Jang		8. Performing Organization Report No. None (E-5923)
		10. Work Unit No. 590-13-51
9. Performing Organization Name and Address Sverdrup Technology, Inc. Lewis Research Center Group 2001 Aerospace Parkway Brook Park, Ohio 44142		11. Contract or Grant No. NAS3-25266
		13. Type of Report and Period Covered Contractor Report Final
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135-3191		14. Sponsoring Agency Code

15. Supplementary Notes

Project Manager, James E. Calogeras, Power Technology Division, NASA Lewis Research Center. Prepared for the 1991 International Solar Energy Conference cosponsored by the American Society of Mechanical Engineers, and the Japan Society of Mechanical Engineers, Reno, Nevada, March 17-22, 1991.

16. Abstract

A grooved water heat pipe was tested to study its characteristics during the cool-down and start-up periods. The water heat pipe was cooled down from the ambient temperature to below the freezing temperature of water. During the cool-down, isothermal conditions were maintained at the evaporator and adiabatic sections until the working fluid was frozen. When water was frozen along the entire heat pipe, the heat pipe was rendered inactive. The start-up of the heat pipe from this state was investigated under several different operating conditions. The results show the existence of large temperature gradients between the evaporator and the condenser, and the moving of the melting front of the working fluid along the heat pipe. Successful start-up was achieved for some test cases using partial gravity assist. The start-up behavior depended largely on the operating conditions.

17. Key Words (Suggested by Author(s)) Start-up Cool-down Water heat pipe	18. Distribution Statement Unclassified – Unlimited Subject Category 34

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of pages	22. Price*
Unclassified	Unclassified	7	A02

*For sale by the National Technical Information Service, Springfield, Virginia 22161